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Tactical athlete training and performance monitoring using motion tape wearable sensors

Yun-An Lin[1,a] and Kenneth J. Loh[1,b,*]

[1] University of California San Diego, Department of Structural Engineering, 9500 Gilman Dr MC 0085, La Jolla, CA 92093-0085, USA

[a] yul095@eng.ucsd.edu, [b,*] kenloh@ucsd.edu

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Abstract. Physical, tactical, and field training are critical for improving warfighter physical performance and capabilities. Exercises and training events are typically supervised; however, group/team training and field exercises lack personalized supervision. While technologies such as optical motion capture (mocap) can capture detailed biomechanics, they are most conveniently used in indoor laboratory settings or in a pre-staged outdoor area. Commercial wearable sensors are readily available, but the data typically correspond to a discrete bodily location and only provide limited information about whether someone is moving, as opposed to how movements are being performed. To fill this gap, a self-adhesive, elastic fabric, nanocomposite skin-strain sensor was developed, extensively tested, and validated through human subject studies. It was found that these "Motion Tape" sensors were not only able to measure skin-strains during functional movements, but its measurements were also correlated with how muscles engage. In this study, Motion Tapes were worn at major muscle groups, and participants performed exercises that simulated military marksmanship training activities. Mocap measurements were also obtained to acquire baseline biomechanical movement data and to quantify typical marksmanship outcomes. Individuals (civilians) were first asked to perform a simulated rifle shooting task (*i.e.*, incorrectly), before being asked to repeat the task (*i.e.*, correctly) after being provided with instructions that targeted improved performance. The results confirmed that Motion Tape skin-strain measurements were able to differentiate between "incorrect" and "correct" movement sequences.

Introduction

Rifle marksmanship is a crucial aspect of military training and qualification, especially for the U.S. Marine Corps. However, training exercises that involve the handling of weapons are not only dangerous and time-consuming, but trainees also rely heavily on individual feedback from an instructor to improve. Such personalized attention and feedback require significant manpower investment and may be difficult to achieve in field exercises or during group sessions. Often, one's marksmanship is assessed according to shot score and/or accuracy [1, 2]. Although using such a quantifiable metric makes sense and may seem objective, a shot score does not provide detailed, actionable information for one to learn from and improve. In fact, poor marksmanship can be caused by movement deficiencies (*e.g.*, sight misalignment or uncoordinated steps during execution) or uncontrolled respiration, which can only be identified visually by a seasoned trainer.

In an attempt to increase training efficiency and decrease time and manpower investments, Chung *et al.* [3] explored the possibility of using multimedia-based instruction, as well as incorporating sensing apparatuses, for improving marksmanship skills and performance. It was found that, while computer-based instruction could increase participants' skills, the extent of improvement was limited. Interestingly, participants that received individualized instruction along with sensor data performed better versus those that did not receive any instruction. These findings are baselined against the fact that no differences were observed between participants who did and

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did not receive individualized instruction without sensor data. Such findings suggested that sensing data can potentially be used by the trainer as a diagnostic tool or can be directly relayed to the trainee in the form of actionable feedback [3].

In another study, sensors were utilized to help objectively quantify metrics that are too subtle to be observed by the naked eye during shooting exercises. For example, Nagashima *et al*. [1, 4] aimed to develop sensor-based skill measures of breath and trigger control. They instrumented a force-pressure sensor on the trigger of the weapon, and participants also wore a respiration belt. With the incorporation of a classification model, it was demonstrated that the sensor-based measurements contributed to a reliable method that could differentiate between expert and novice marksmanship skills. However, marksmanship involves more than respiration and trigger pull to include limb and body movement control, especially in more complicated shooting scenarios [5, 6].

Therefore, the objective of this study was to test the hypothesis that body movement measurements provide rich information about marksmanship performance. Movement measurements were obtained using a self-adhesive, elastic fabric, wearable sensor called "Motion Tape." Previous studies showed that Motion Tape can be mounted on practically anywhere on the body to acquire accurate skin-strain measurements. This paper begins with a brief explanation of how Motion Tape was fabricated and its working mechanism, followed by a summary of sensor performance characterization based on prior laboratory load frame and human subject testing. Next, the human subject marksmanship test protocol, which involved participants wearing Motion Tape, is explained in detail. Then, the results from the human subject tests are shown and analyzed. This paper concludes with a brief summary and discussion of how Motion Tape can be employed to enhance marksmanship training in the future.

Experimental Details

Motion Tape Fabrication and Characterization. A low-profile, self-adhesive, elastic fabric, nanocomposite skin-strain sensor – Motion Tape – was designed and fabricated for human movement and muscle engagement monitoring. In essence, a graphene nanosheet and ethyl cellulose dispersion was formulated and spray-coated as is onto commercial off-the-shelf kinesiology tape (K-Tape) to produce these piezoresistive Motion Tape skin-strain sensors. Electrodes were established at opposite ends of each nanocomposite sensing element by depositing conductive silver ink, followed by soldering multi-strand wires. A schematic of the fabrication process is shown in Fig. 1a, and the detailed fabrication procedure is described in Lin *et al*. [7]. Fig. 1b shows a typical Motion Tape sample used for testing.

A comprehensive electromechanical sensor characterization study was conducted by subjecting Motion Tape samples to tensile cyclic load frame tests. The results showed that Motion Tape exhibited stable, linear, low-hysteresis, and high-sensitivity response, with repeatable linear-elastic strain sensing properties up to ~12%. Furthermore, it is worth noting that its strain sensitivity can be tailored between 10 and 100 depending on the specific graphene nanosheet ink

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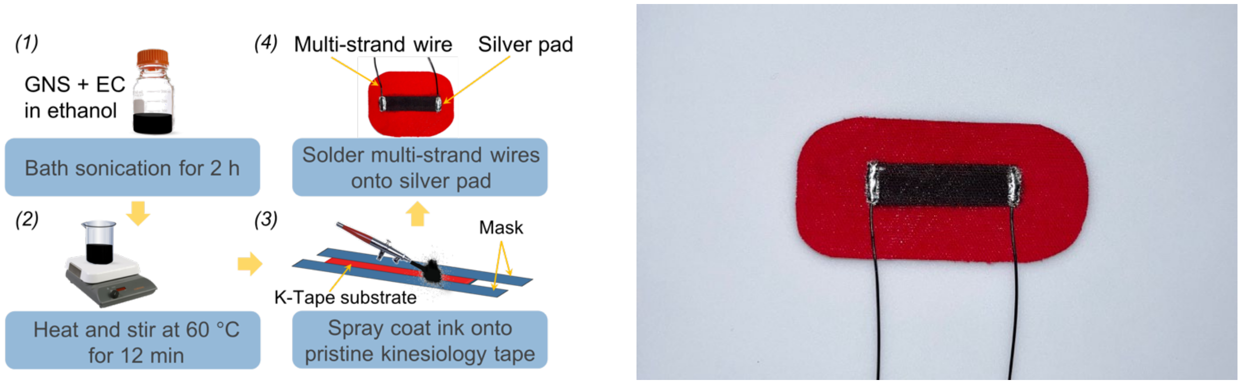
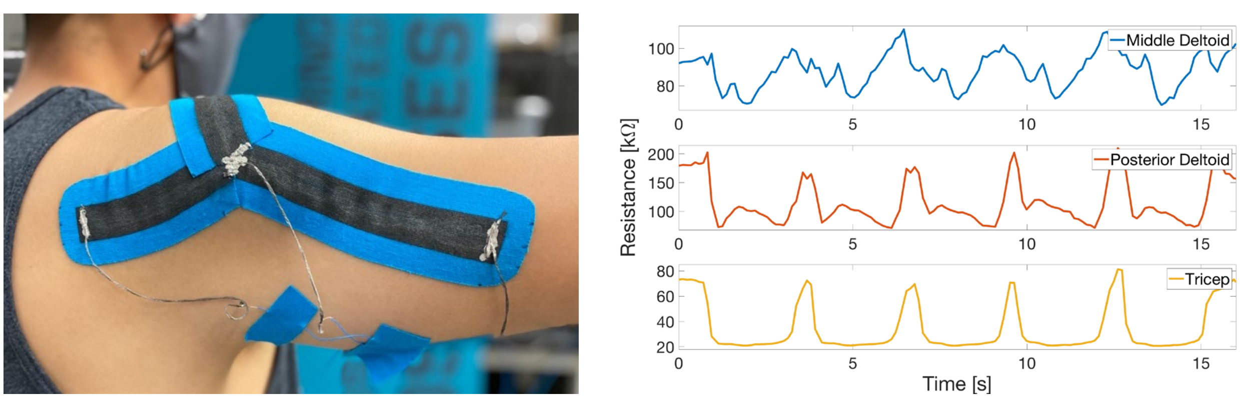


(a) (b)

Figure 1. (a) A schematic of the fabrication process of Motion Tape and (b) a Motion Tape sample is shown.

formulation and fabrication parameters used. The laboratory characterization results can be found in Lin *et al.* [7].

Human subject tests with participants wearing Motion Tapes over major muscle groups (*e.g.*, biceps, quadriceps, and trapezius) were also performed. Motion Tape were applied as individual sensors, or they can be applied together to form a unique pattern to cover desired muscle groups, such as the 'Y' pattern that covered the triceps, middle deltoid, and posterior deltoid, as shown in Fig. 2a. To demonstrate muscle engagement monitoring in this test, the subject performed side shoulder raises five times, while a data acquisition system (Keysight 34401A digital multimeter) was used to simultaneously measure and record the electrical responses from each of the three Motion Tape sensing elements. From Fig. 2b, it is clear that Motion Tape resistance measurements can capture unique waveforms of how the muscle groups engaged in order to produce functional movements. In fact, Lin *et al.* [8] showed that Motion Tape resistance measurements were highly correlated with skin-strains estimated using a Vicon optical motion capture (mocap) system that tracked the relative displacement between two retroreflective markers mounted adjacent to Motion Tape. In addition, the high sensitivity of Motion Tape allowed it to capture very small skin-strain differences associated with different extents of muscle engagement during functional movements. Previous studies found that greater changes in electrical resistance were measured when participants performed biceps curls using heavier weights. Overall, these results demonstrated that



(a) (b)

Figure 2. (a) A 'Y' pattern Motion Tape Network was affixed onto the subject's upper arm/shoulder area. (b) Electrical resistance measurements were acquired while the subject performed side shoulder raises, and the results are shown.

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Motion Tape is a versatile wearable sensor that can be used to measure how functional movements are performed.

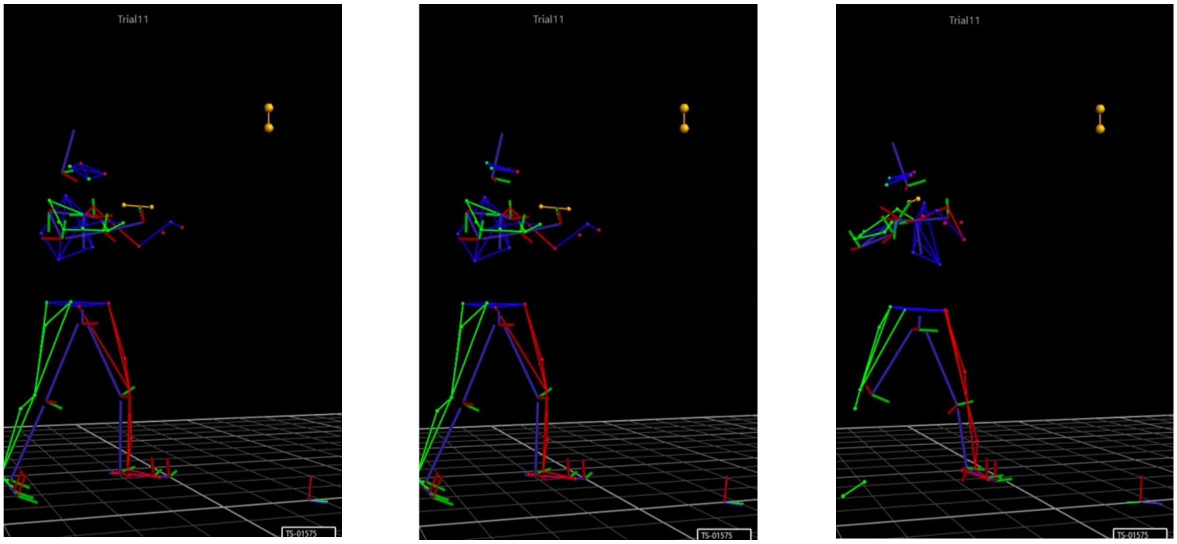
Marksmanship Human Subject Test Protocol. In this study, a simulated marksmanship training exercise was designed and conducted in the laboratory. The participant was asked to emulate the process of aiming and shooting at a target located 90º on the right of the individual. The entire movement sequence started with the participant standing still while holding an M4 rifle replica. The rifle was then raised, while facing forward, so that its stock rested on the chest and the participant could see and aim through the sights without any significant head tilt. Then, the first set of movements corresponded to the "untrained" or "incorrect" movement sequence. The participant first turned his head towards the right side to identify the target, before rotating his upper body and rifle to aim at the target. On the other hand, the second set of movements, after being coached with verbal instructions, corresponded to the "trained" or "correct" movement sequence. With the rifle pointed forward, the participant was instructed not to turn his head but instead rotate his entire upper body and rifle in unison to then aim at the target. In this movement sequence, the participant's head was always pointed in the direction of the rifle. For both cases and upon successfully aiming at the target, the reverse sequence of movements was performed to return to the original standing posture. Fig. 3a and 3b show full body optical motion capture snapshots corresponding to the incorrect and correct movement sequences, respectively. In essence, the main movement difference lies in whether the participant rotated his head/neck.

Motion Tape and Marker Placement. During the aforementioned marksmanship human subject tests, each participant wore five Motion Tapes and was also outfitted with a full body set of retroreflective mocap markers. First, two Motion Tapes were placed, one each, on the left and right deltoid. Motion Tape was also affixed near the left and right trapezius, as well as one on the trigger finger. Fig. 4a and 4b show pictures of where Motion Tapes were mounted on the participant. Second, a 12-camera Vicon optical motion capture system was employed to measure the kinematic movements of the participant during testing, as is shown in Fig. 4c. The 3D positions of the retroreflective markers were recorded at 100 Hz. In addition, Motion Tapes were connected to the Vicon Lock Lab analog interface so that time-synchronized electrical resistances (*i.e.*, through the use of voltage dividers) could be acquired. The Motion Tape signals were conditioned and filtered using a fourth-order Butterworth low-pass filter with a cut-off frequency of 60 Hz. Last, two retroreflective markers were also mounted on the target (*i.e.*, with its midpoint defined as the bullseye), and two additional markers mounted along the rifle barrel were used to define the linear shot trajectory.

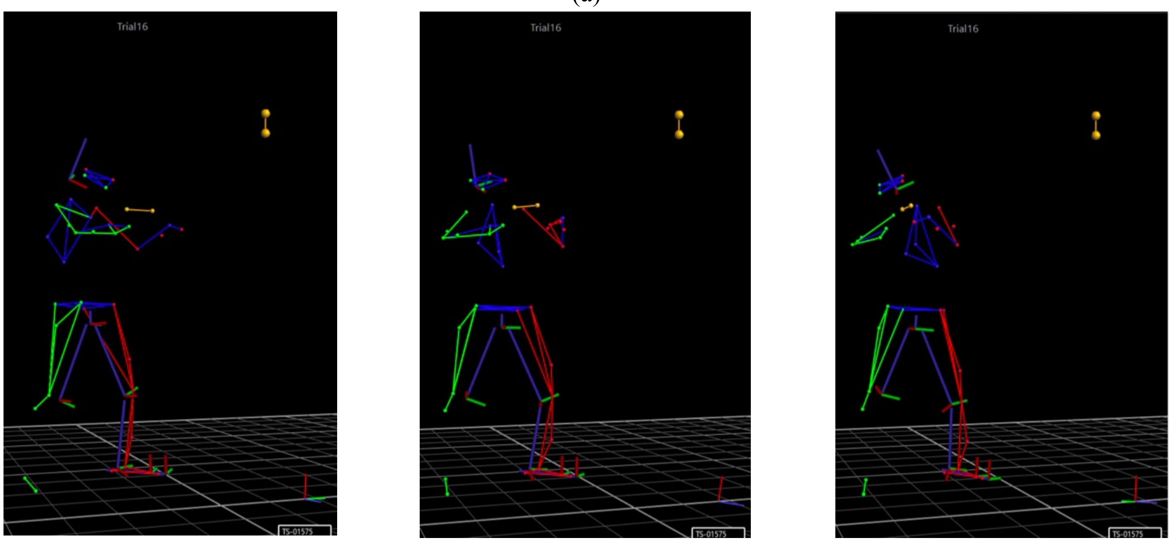
Results and Discussion

The results of the simulated marksmanship tests are shown in Fig. 5. Fig. 5a corresponds to the measurements acquired when the incorrect movement sequence was performed, while Fig. 5b was for the correct movement sequence. To visualize and be able to directly compare the Motion Tape sensing streams, the normalized change in electrical resistance (ΔR_n) was calculated and plotted with respect to time.

$$\Delta R_n = \frac{R_i - R_0}{R_0} \tag{1}$$



(a)



(b)

Figure 3. Optical motion capture image frames of (a) an incorrect rifle shooting posture (i.e., head turning before body rotation) versus (b) a correct shooting posture (i.e., head turning together with body rotation) are shown.

where R_i is the resistance of Motion Tape at any time instance, and R_0 is its nominal resistance (*i.e.*, the baseline resistance of Motion Tape when the subject was standing still in a neutral position).

When compared against one another, it can be observed that, prior to marksmanship instruction (*i.e.*, incorrect movement sequence), Motion Tape data from both the deltoids and the trapezius muscles showed large variability during target identification and aiming. In contrast, Motion Tape data at these same locations showed significantly smaller variability and more stable responses for the correct movement sequence. This smaller variability was expected, since the correct movement sequence corresponded to the participant not rotating his head during target identification. These results confirmed that Motion Tape possessed sufficient sensitivity to capture these small movement differences.

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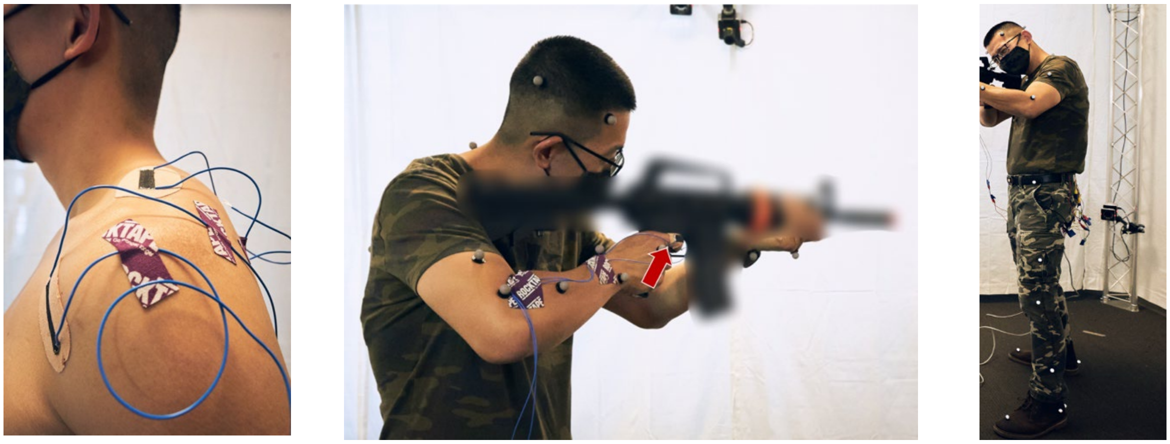
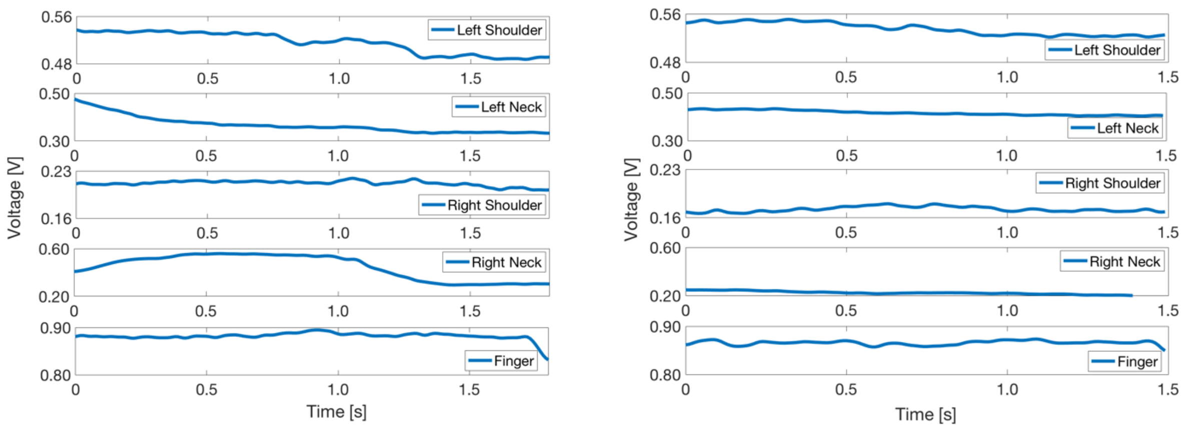


(a) (b) (c)

Figure 4. (a) Two pairs of Motion Tapes were affixed on the left and right side of the neck and shoulder region, as well as (b) a Motion Tape on the trigger finger, as indicated by the red arrow. (c) A full-body retroreflective marker set was used to capture kinematic movements.



(a) (b)

Figure 5. (a) Motion Tape measurements during an incorrect rifle shooting posture versus (b) the correct shooting posture are compared.

The mocap data collected during the simulated marksmanship tests were also analyzed. In particular, the two retroreflective markers on the rifle barrel were used to define a linear line, and its direction was assumed to be the shot trajectory or aim of the rifle. Shot accuracy – or more specifically inaccuracy – was also calculated by comparing the deviation of the shot trajectory with respect to the midpoint of the target. The results showed that prior to instruction, inaccuracy was 73.3 ± 20.2 mm; after instruction and by performing the correct movement sequence, inaccuracy decreased to 52.2 ± 29.1 mm. These results confirmed that the correct movement sequence yielded better marksmanship performance.

Finally, shooting speed was quantified as the time from the start of movements to when the participant pulled the trigger. Analysis of the mocap and trigger finger Motion Tape results showed that it took the participant 1.94 ± 0.10 s to pull the trigger when the incorrect movement sequence was performed. After instruction, the correct movement sequence resulted in faster behavior, taking only 1.38 ± 0.19 s. Overall, the accuracy and speed results demonstrated that performing the correct movement sequence yielded improved marksmanship performance. Motion Tape

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measurements of skin-strains near the deltoid and trapezius muscle groups showed observable differences between correct versus incorrect movements.

Based on the data collected from the marksmanship tests, Motion Tape sensing streams can potentially provide the trainer and trainee with movement specific data that cannot be readily obtained using commercial off-the-shelf wearable sensors. Unlike mocap, Motion Tape does not have to be used in a laboratory setting and can be potentially used in field exercises where it would be difficult or impractical to install mocap cameras. Furthermore, it was previously shown that Motion Tape measurements are correlated with the degree of muscle engagement [9]. Such detailed information about movement and muscle engagement means that Motion Tape can provide muscle-specific feedback to help guide individuals about how to alter the execution of functional movements that lead to improved performance.

Conclusions

In this study, a stretchable, elastic fabric, skin-strain sensor (*i.e.*, Motion Tape) was employed to monitor subtle human movements during simulated marksmanship training exercises. Its simple fabrication process, as well as ease of application onto the human body, made Motion Tape an appropriate sensing apparatus for monitoring human movements during complex activities such as shooting a rifle. During the experiment, the participant wore Motion Tapes at key locations on the upper body, in addition to mocap retroreflective markers, which were used as reference for verification. The results showed that each Motion Tape was able to acquire disparate waveforms before and after verbal instructions, where the overall variation of signal amplitudes was reduced after performing movement sequences correctly, indicating steadier postures and hence better performance. Further, analysis of the mocap data showed that, after receiving instructions on proper marksmanship, the participant achieved faster and more accurate target aiming.

Overall, this study demonstrated that the use of Motion Tape during training could help provide feedback on how one performs functional movements, which is something that most wearable sensors today cannot do. The long-term goal of this work is to use sensing streams from a limited number of Motion Tapes as inputs for a machine learning method to infer how one moves and how those movements affect performance. The vision is that this technology can facilitate efficient and effective training by providing actionable feedback and diagnostic information for both trainers and trainees. Future work will focus on improving the linear sensing range of Motion Tape as well as miniaturization of the portable data acquisition system.

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